

Self-Raman Nd:YVO4 laser and electro-optic technology for space-based sodium lidar instrument

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ABSTRACT

We are developing a laser and electro-optic technology to remotely measure Sodium (Na) by adapting existing lidar technology with space flight heritage. The developed instrumentation will serve as the core for the planning of an Heliophysics mission targeted to study the composition and dynamics of Earth's mesosphere based on a spaceborne lidar that will measure the mesospheric Na layer. We present performance results from our diode-pumped tunable Q-switched self-Raman c-cut Nd:YVO4 laser with intra-cavity frequency doubling that produces multi-watt 589 nm wavelength output. The c-cut Nd:YVO4 laser has a fundamental wavelength that is tunable from 1063-1067 nm. A CW External Cavity diode laser is used as a injection seeder to provide single-frequency grating tunable output around 1066 nm. The injection-seeded self-Raman shifted Nd:VO4 laser is tuned across the sodium vapor D2 line at 589 nm. We will review technologies that provide strong leverage for the sodium lidar laser system with strong heritage from the Ice Cloud and Land Elevation Satellite-2 (ICESat-2) Advanced Topographic Laser Altimeter System (ATLAS). These include a space-qualified frequency-doubled 9W @ 532 nm wavelength Nd:YVO4 laser, a tandem interference filter temperature-stabilized fused-silica-etalon receiver and high-bandwidth photon-counting detectors.

Keywords: Sodium lidar, Nd:YVO4 laser, space-based science instruments, optical filters

1. EARTH MESOSPHERIC SCIENCE

In recent years, remote-sensing satellites have obtained the first global characterization of the basic structure of the Mesosphere and Lower Thermosphere (MLT) region in terms of large-scale temperature and wind climatologies, resulting in a much richer picture of the structure and variability of the mesosphere. Although these measurements have shown the high temporal variability of both the zonal mean state as well as large scale organized perturbations, such as planetary waves and atmospheric tides, they failed at providing information required for the fundamental characterization of how the basic state is established and maintained.

Layers of neutral metal atoms, such as Iron (Fe), Magnesium (Mg), Calcium (Ca), Potassium (K) and Sodium (Na), which peak between 85 and 95 km and are ~20 km in width, are produced by the daily ablation of billions of Interplanetary Dust Particles (IDPs). As these metallic species are ionized during ablation, by sunlight's ultraviolet photons, or by charge exchange with existing atmospheric ions, meteoroids affect the structure, chemistry, dynamics, and energetics of the Mesosphere and Lower Thermosphere (MLT). The strong optical signals that some of these metal layers produce, in particular the Na layer, provides information on the composition, temperature and winds of the MLT making them an optimal tracer of atmospheric dynamics and circulation and potentially enabling the measurement of quantities that are critical to address several compelling scientific questions related to the Earth's Upper Atmosphere and the Geospace Environment. Specifically, we know that Gravity waves (GWs) having wavelengths smaller than a few hundred km are the dominant contributors to momentum transport and deposition in the MLT, which largely drive the global circulation and thermal structure and interactions with the tides and planetary waves in this region. However, predicting their impact on atmospheric chemistry and dynamics is a major uncertainty in current atmospheric models. Thus there is a pressing need in the ITM community to be able to perform high-resolution measurements that can be used to characterize these waves and their effects in the MLT on a global basis. Such measurements must include highly resolved, in space and time, global temperature and wind profiles, as well as the global distribution of GWs (e.g different orographic forcing sources) and their spectra, which will add to the understanding of key indicators of radiative cooling in the mesosphere.

Our goal is to develop a spaceborne remote sensing technique that will enable acquisition of global Na density, temperature and wind measurements in the MLT with the spatial and temporal resolution required to resolve issues associated with the structure, chemistry, dynamics, and energetics of this region. Over four decades of ground-based and over two of airborne Na and Fe lidar observations^{1,2,3,4} have demonstrated that this technique is ideal to obtain high-resolution measurements of these quantities. Unfortunately, while these lidars provide very high temporal and vertical resolutions measurements, the ground-based sites are geographically sparse and cannot provide representative global climatologies. Recent models of the mesospheric Na layer⁵ have shown large variations in the sodium constituents over timescales from days to months. These studies also demonstrated that measuring the Na layer at a global scale can enable the study of how external sources impact this region. For example, short-term response of the upper atmosphere to a stratospheric sudden warming is clearly revealed in the sodium column. Seasonality of sodium constituents is strongly affected by variations^{6,7} in the Meteor Input Function (MIF) and transport via the mean meridional wind. Thus, it is clear that global high-resolution measurements capabilities of the Na layer using resonance fluorescence lidar will permit, not only measurements of zonal mean structures, planetary waves and tides, but also uniquely characterization of the global distribution of GWs. Such measuring capabilities will enable more accurate constrain of Global Circulation Models (GCMs) via GW drag parameterization enabled by the global estimation GW forcing and transport. Additionally, measuring the global distribution and variability of meteoric Na that will enable to constrain models of the MLT chemistry, meteoroid ablation and mass loss processes, and Zodiacal Dust Cloud as well as their impact in planetary atmospheres⁸.

A zenith pointing Na Doppler lidar would provide measurements of vertical profiles of absolute temperature, absolute Na density and vertical wind perturbations. These data would enable the global characterization of the mesopause region temperature and Na density structure as well as gravity wave variances and spectra. In addition it would be possible to characterize wave-induced vertical transport of Na and other mesopause region species by computing the vertical Na flux profiles and perhaps the heat flux profiles⁹. Vertical constituent transport by gravity waves plays a crucial role in mesopause region chemistry which establishes the structure and seasonal variations of key species such as odd-oxygen. By restricting wind observations to the vertical wind perturbation profiles, rather than absolute winds, the nadir pointing accuracy and stability of the instrument can be relaxed. A more sophisticated scenario is one that will have two beams pointing off zenith in an orthogonal configuration and one beam pointing zenith so that temperature, vector wind and Na density can be measured simultaneously and globally with very high resolution and accuracy. This would further enhance the scientific benefits of the experiment, including the direct measurements of gravity wave momentum flux.

2. SODIUM LIDAR DEVELOPMENT PATH

Our science goal is to measure range-resolved atmospheric-sodium-temperature profiles from Low-Earth-Orbit (LEO) using a space-based lidar. The atmospheric temperature is deduced from the linewidth of the resonant fluorescence from the atomic sodium vapor D2 line as measured by a tunable laser as shown in Fig. 1.

As noted earlier, tunable pulsed ground-based Na lidar systems have provided some mesospheric temperature and wind profiles. However, the key components of the present ground-based sodium lidar systems are not readily transferred to a space-based sodium lidar. Fortunately, a large number of the sodium lidar components are similar to those developed under the NASA Earth Science ICESat-1/GLAS, ICESat-2/ATLAS and pre-Phase-A ASCENDS Instrument Incubator Program missions. Our thesis is that this leverage and experience can provide a quick path to a space-based sodium lidar science instrument.

2.1 Sodium lidar laser transmitter

The key sodium lidar component that requires some development and integration into a lidar system demonstration is the laser transmitter.

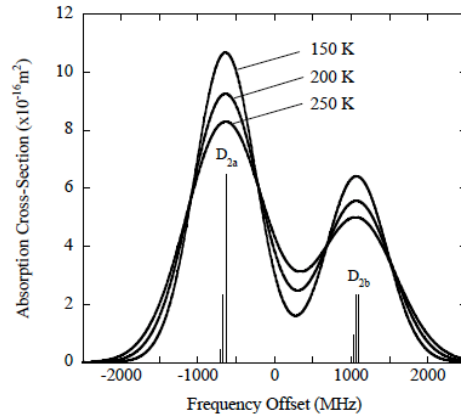


Fig. 1. The D2 resonance line is a Doppler broadened doublet composed of six hyperfine lines of atomic sodium at 589.159 nm wavelength. The Doppler broadening of the lines is a function of temperature and the ratio of the D2a peak to the value at the minimum between the peaks is a very sensitive function of temperature. (from Reference 10.)

Under a NASA-GSFC IRAD, we conducted a trade study on various approaches for laser development to measure mesospheric sodium. The laser requirements are listed in Table 1.

Wavelength (nm)	589.2 nm \pm 0.3 nm
Optical Power (@589 nm)	9 W
Pulsed	Yes
Wall-plug efficiency	>2%
Pulse width	1 - 50 ns
Spectral width	< 100 MHz
Tuning range	0.5 nm
Tuning speed	< 10 microseconds per GHz
Beam Quality (M ²)	< 4
Spaceflight heritage	Yes

Table 1. Sodium lidar laser requirements

Two approaches allow some leverage from previous space-qualification work, 1) mixing the output of two Nd:YAG lasers – one at 1064 nm and one at 1310 nm; 2) A frequency-doubled self-Raman shifted Nd:YVO₄ laser¹¹. The ICESat-2/ATLAS mission has a fully space-qualified frequency-doubled Nd:YVO₄ laser transmitter¹² with 9 Watts of output at 532 nm (Figure 2). Since the self-Raman shifted Nd:YVO₄ laser only requires one laser that is very similar to the ICESat-2 ATLAS laser with very few non-space-qualified components – we selected it over the two Nd:YAG laser approach. A diagram of our sodium lidar laser approach is shown in Figure 3. We use a c-cut Nd:YVO₄ crystal to produce tunable laser light from 1062.2 - 1066.7 nm (rather than the a-cut which lases at 1064 nm). A typical c-cut Nd:YVO₄ tuning curve¹³ is shown in Figure 4. An active Q-switch is used to produce high-peak-power pulses to exploit a non-linear self-Raman shift to 1178 nm wavelength in the exact same crystal. The Q-switching provides the time-of-flight pulses for range-resolved atmospheric temperature measurements while also increasing the intra-cavity frequency-doubling efficiency for 589 nm wavelength output generation. A tunable injection seeding 1066 nm wavelength diode laser allows us to tune the Nd:YVO₄ laser to (and across) the exact sodium D2 line. The injection seeding allows rapid all-electronic wavelength tuning.

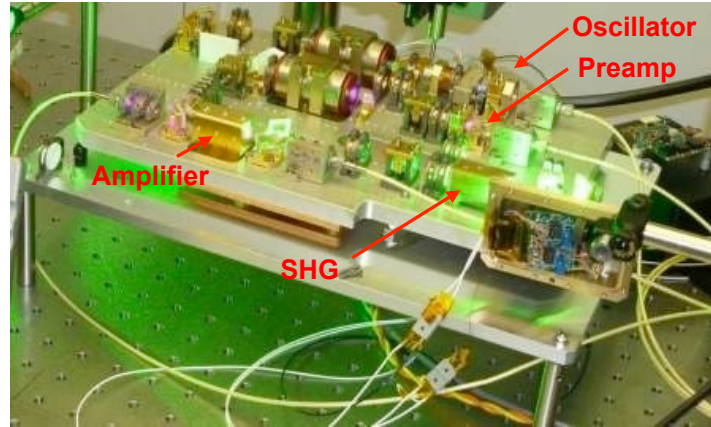


Fig. 2. Brassboard ICESat-2/ATLAS 9 W Nd:YVO₄ laser transmitter (courtesy of Fibertek Inc.)

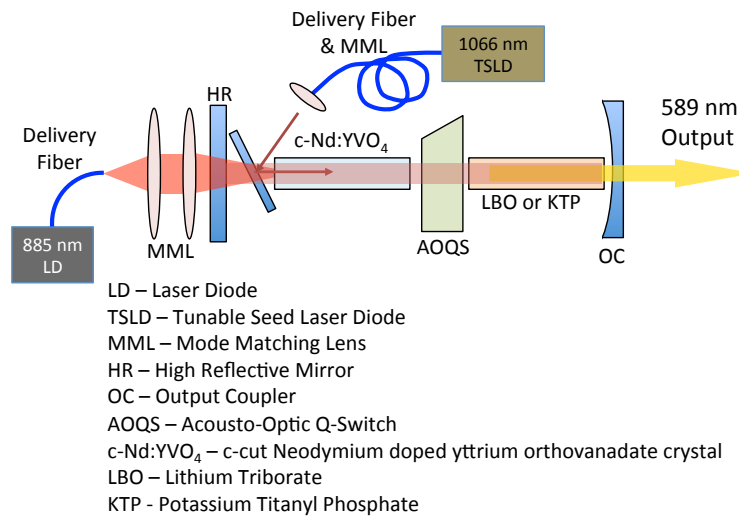


Fig. 3. Sodium lidar injection-seeded Nd:YVO₄ laser transmitter diagram

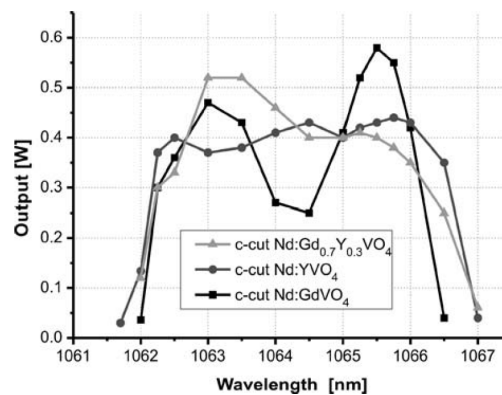


Fig. 4. Wavelength tuning curve for Nd:YVO₄ (and two related) laser transmitters (Ref. Sirotkin)

Referring to Figure 1, the tuning range needed to profile the entire sodium fluorescence spectrum is 4 GHz. The equivalent wavelength range at 589 nm for this 4 GHz frequency range is 4.6 pm. We will wavelength lock the injection seed laser to an absolute wavelength to within 4 MHz of the center of the D2 lines, then using injection current we can tune the laser over the ± 2 GHz (± 2.3 pm) range to profile the sodium spectrum.

We have constructed a breadboard Self-Raman Nd:YVO₄ laser (Figure 5). To date, we have achieved ~0.5 Watts of optical power output at 589.4 nm wavelength with 15 Watts of diode pump power. For this proposed effort, we will demonstrate 9 W of 589 nm output that is needed for spaceborne application.

Our laser breadboard is based on c-cut Nd:YVO₄ emitting at 1066.6 nm then self Raman shifted to 1178 nm and intracavity frequency doubled to 589 nm. The laser transmitter breadboard is shown in Figure 4, the laser is pumped by a fiber coupled 808 nm laser diode. This is used to end pump a c-cut 0.3% atomic-weight Nd doped vanadate gain medium and a dimension of 3 mm x 3 mm x 20 mm.

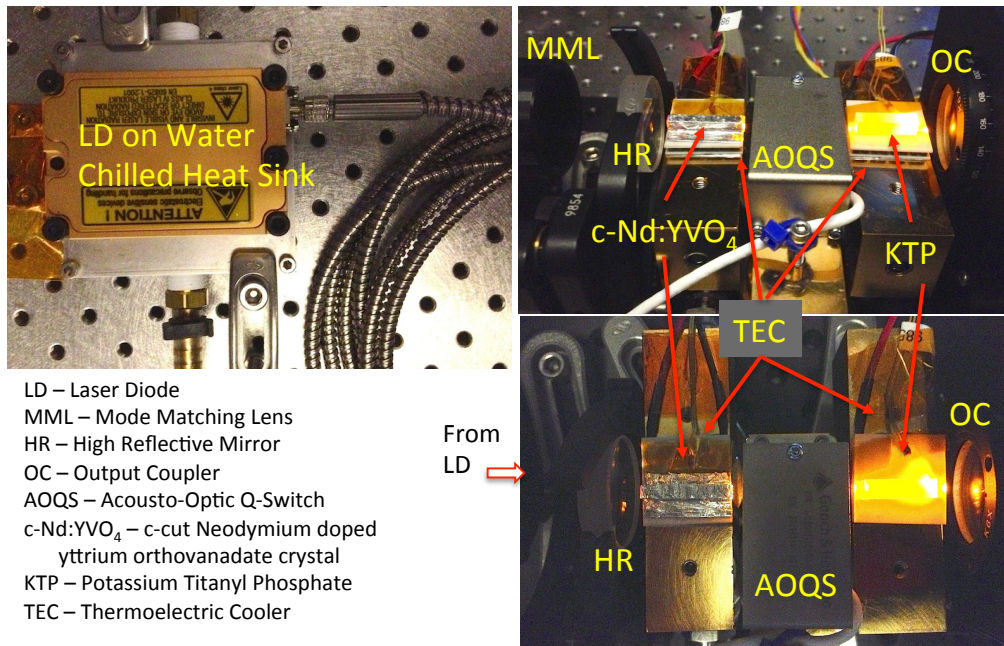


Fig. 5. NASA-GSFC breadboard Self-Raman Q-switched Nd:YVO₄ frequency-doubled laser with 589 nm output.

The laser crystal is wrapped with an indium foil and bonded to a thermoelectric cooler (TEC) for efficient cooling and thermal management. A thermistor located on the side of the laser crystal is used to measure the crystal surface temperature and provide feedback to the temperature feedback loop to maintain the laser crystal to 20°C. An acousto-optic active Q-switch (AOQS) is used to produce high peak power pulses that enables us to use the self-Raman effect in the exact same crystal to produce a laser at 1178 nm and enhances the frequency-doubling efficiency to 589 nm. A Lithium Triborate (LBO) or Potassium Titanyl Phosphate (KTP) crystal is used for intracavity frequency doubling. The KTP is also bonded to a TEC for temperature control for type II critical phase matching at 300 K. In Figure 6, we show the spectra of our laser breadboard output. The 1066 nm and the 1178 nm leak out of the laser cavity and traveled collinearly with the 589 nm output beam.

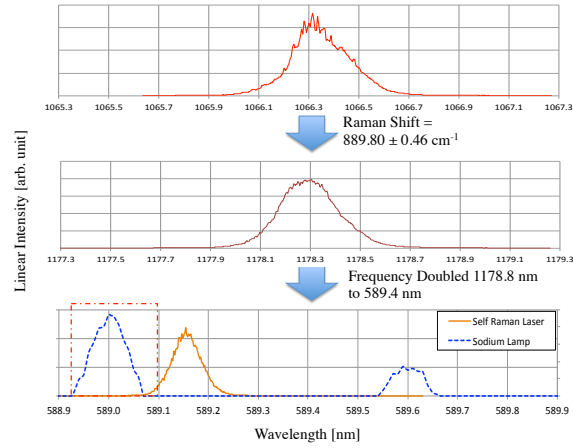


Fig. 6. Measured optical spectra of the NASA-GSFC self-Raman, intracavity frequency-doubled laser breadboard with (not yet tunable) output at 589.4 nm superimposed with the measured spectra of our sodium vapor lamp. We will optimize the lidar system for the boxed sodium D2 line centered at ~ 582.2 nm.

2.2 Laser Wavelength - Locking for Atomic (or Molecular) Spectroscopy

To tune the wavelength of the Nd:YVO4 laser to the sodium D2 line, we will use injection seed with a tunable Distributed FeedBack (DFB) laser diode at 1066.55 nm. As shown in Fig. 7, we have demonstrated (Numata et al., 2012) a precision and fast wavelength tuning technology that allows a wavelength-locked laser to rapidly scan across an atomic/molecular (e.g. CO₂ or Na) absorption line at a user-selectable number of precise wavelengths for remote atmospheric spectroscopy measurements. Our approach uses a master laser that is wavelength-locked to the atomic (or molecular) line center by using a frequency modulation technique, limiting its frequency drift (one standard deviation) to 60 kHz at 0.8-sec averaging time over 72 hours (Numata et al., 2011).

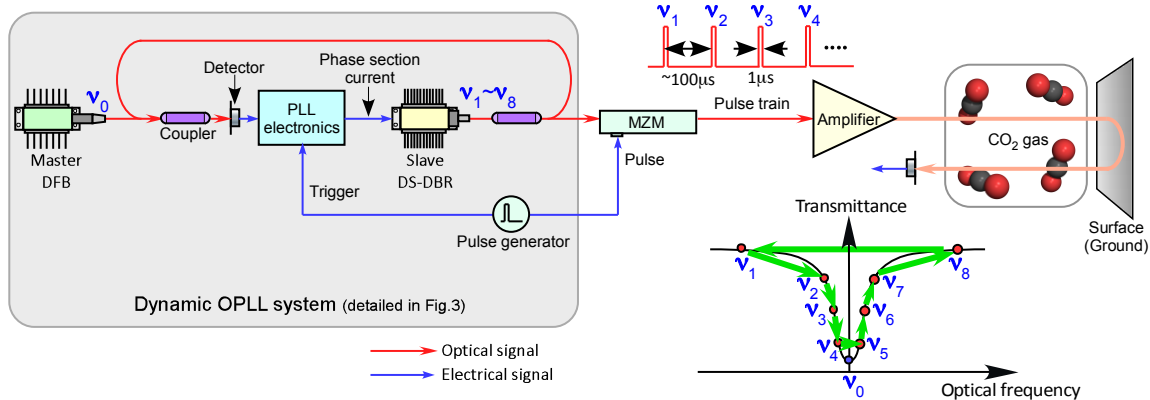


Fig. 7. Concept of the precision fast laser tuning technology and its application for CO₂ (or Na) remote sensing. The slave laser is dynamically offset-locked to the master DFB-LD using an OPLL. The wavelength- stepped pulse train is formed by external modulation through the MZM and subsequent amplification. The amplified pulse train is used to repeatedly measure at multiple points across the CO₂ (or Na) absorption line.

A second (a.k.a. slave) laser diode is dynamically offset-locked to the master laser diode by using an optical phase-locked loop (OPLL), enabling precision fast-tuning of the slave laser to and from any frequencies within a 40-GHz tuning range. For sodium spectroscopy, the master laser is 1178.4 nm that is doubled to 589.2 nm and wavelength-locked to a sodium vapor cell. The offset-locked slave laser is the tunable 1066.55nm injection seeder. The OPLL suppresses any slow drift of the offset frequency, allowing the slave laser to retain the absolute frequency stability of the

master laser. The frequency-stepped pulse train is formed by external modulation through a Mach-Zehnder modulator (MZM) and subsequent amplification. Our technology satisfies stringent requirements for atmospheric gas sensing lidars and enables other applications that require such well-controlled precision fast tuning.

A patent application has been filed for this technology by NASA-GSFC.

2.3 Ultra-Narrow-Band Optical Filter

We developed space-qualified ultra-narrow (28 pm) optical filters³ for both the ICESat-1/GLAS and ICESat-2/ATLAS missions and a derivative similar filter was used on the CALIPSO mission. An atomic sodium Faraday filter (Yong et al., 2011) may provide economic and performance benefits over the etalon filter. We are studying the use of both etalon and atomic sodium filters with 5-10 pm optical bandwidth to enable some daytime sodium lidar observations.

2.4 Detector

Our space-flight-precursor photon-counting detector technology¹⁴ is a 16-channel Photomultiplier Tube with receiver electronics that has been space-qualified for the ICESat-2/ATLAS mission. Our technique uses the 16-channels as a photon-number-resolving “single” detector to provide the required full-spectroscopic sodium lineshape waveform for recovering Mesospheric temperature profiles. We have direct experience using photon-counting receivers for recovering high signal-to-noise ratio single line spectroscopic profiles from our ground¹⁵ and airborne¹⁶ pre-ASCENDS mission efforts. Under the proposed effort we will conduct trade studies with the commercial 40% quantum-efficiency Hamamatsu linear-mode hybrid photomultiplier and new multi-channel silicon avalanche photodiodes similar to those space-qualified by us¹⁷ on the ICESat-1/GLAS mission. These newer alternate detectors may provide economic and performance benefits over the PMT.

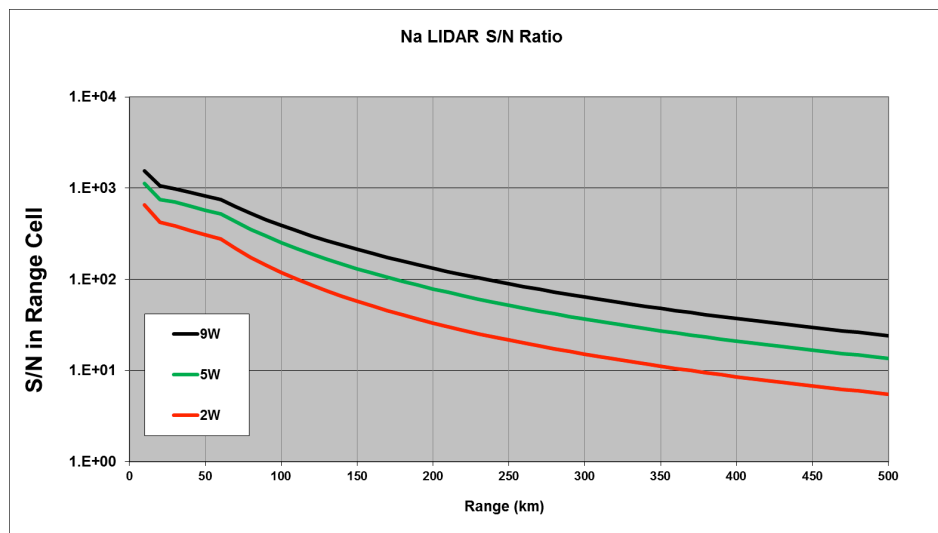


Fig. 8. Sodium Lidar S/N ratios for 1 kHz laser pulse rate and the optical background spectral irradiance of 263 W/m²/μm of averaged Earth albedo (0.31) vs. Sun at 45 degrees.

2.5 Link Analysis

Several studies have been conducted analyzing component and performance requirements for space-based sodium lidar⁴. The numerical estimation of the optical power, telescope aperture, detection system and spectroscopic temperature recovery performance is sometimes referred to in the lidar community as a link analysis – borrowing the term from optical communication links. Our own link analysis has been consistently verified by numerous past ground, airborne and space lidar missions. Our preliminary link analysis for a space-based sodium lidar is shown in Figure 8 and Table 2. With a space-based 9 Watt laser optical output at 589.2 nm, a 0.8-meter optical receiver telescope and a photon-counting receiver, we estimate that we can retrieve global mesospheric temperature profiles with the required temporal (~30 s),

altitude ($\sim 1\text{--}2$ km), temperature ($\sim 1\text{K}$) and wind velocity ($\sim 1\text{--}5$ m/s) resolution to achieve unprecedented MLT science. Our third-year operational space-flight- precursor ground-based sodium lidar will allow us to directly verify our lidar link analysis by comparing to experimental results to greatly improve extrapolation to a moving Low-Earth-Orbit space-based platform.

9 W Laser Pulse Rate (Hz)	Nominal Operational Scenario: S/N for 263 W/m²/μm optical background	Worst Case Operational Scenario: S/N for 1000 W/m²/μm optical background
1	125	123
10	119	106
100	87.8	56.3
1000	37.1	19.7
10000	12.9	6.3

Table 2: Predicted Signal to Noise ratios (S/N) of the spaceborne Na-lidar equipped with 9 W, 589 nm pulse operated laser and 0.8 m receiver telescope with 0.1 mrad field of view, 100 m range resolution and 10 s time integration under nominal and worse case optical backgrounds equivalent to 263 and 1000 W/m²/μm respectively.

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